ELSEVIER

Fusion Engineering and Design 32-33 (1996) 493-502

Fusion Engineering and Design

Plasma lens focusing and plasma channel transport for heavy ion fusion

A. Tauschwitz[a], S.S. Yu[a], S. Eylon[a], R.O. Bangerter[a], W. Leemans[a], C. Peters[a], J.O. Rasmussen[a], L. Reginato[a], J.J. Barnard[b], W.M. Sharp[b]

[a]*Lawrence Berkeley National Laboratory, 1 Cyclotron Raod, Berkeley, CA 94720, USA*
[b]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

Abstract

The capabilities of adiabatic, current-carrying plasma lenses for the final focus problem in heavy-ion-beam-driven inertial confinement fusion are explored and compared with the performance of non-adiabatic plasma lenses, and with that of conventional quadrupole lenses. A final focus system for a fusion reactor is proposed, consisting of a conventional quadrupole lens to prefocus the driver beams to the entrance aperture of the adiabatic lens, the plasma lens itself, and a high current discharge channel inside the chamber to transport the focused beam to the fusion pellet. Two experiments are described that address the issues of adiabatic focusing, and of transport channel generation and stability for ion beam transport. The test of the adiabatic focusing principle shows a 26-fold current density increase of a 1.5 MeV potassium ion beam during operation of the lens. The lens consist of a discharge of length 300 mm, filled with helium gas at a pressure of 1 Torr and is pulsed with a current between 5 and 15 kA. The investigations of discharge channels for ion beam transport show that preionization of the discharge channels with a UV laser can be an efficient way to direct and stabilize the discharge.

1. Introduction

The final focus lens for a heavy-ion-beam-driven inertial confinement fusion (ICF) reactor is a crucial component for the whole driver–reactor system. The capabilities of this final lens determine the requirements for the quality of the driver beams; they have a strong impact on the construction of the reactor chamber and they even influence the design of the fusion target. Important parameters of the final focus lens are the maximum beam current that can be focused in a single lens, the sensitivity to longitudinal and transversal beam emittance, the aperture of the lens, and the ratio by which the beam radius can be reduced with the lens. Various focusing schemes have been proposed and studied [1]. They differ in the charge state of the ions, the vacuum requirements in the reactor chamber, and the physical mechanism of the beam transport through the reactor chamber. The most important difference between the focusing schemes is the degress of space charge and current neutralization in the lens. Non-neutralizing lenses require a low charge state

0920-3796/95/$15.00
PII S0920-3796(96)00505-4

of the ions, a high vacuum in the reactor chamber and a limited beam current per lens, for example. In contrast, neutralizing lenses are insensitive to the ion charge state, allow or require higher pressure in the discharge chamber, and can focus almost unlimited beam current in a single lens.

2. Plasma lens focusing concepts

The above-mentioned characteristics of neutralizing lenses make them particularly interesting for ICF applications. All these lenses are often summarized under the term 'plasma lens', since a plasma is required to provide the space charge neutralizing electrons. In the case of a passive plasma lens, preparation of free electrons is the only function of the plasma. The advantage of this passive lens is simplicity, especially when the plasma is created through the ionization of a background gas by the ion beam itself. The disadvantage of a passive lens is the dependence of the focusing on the quality and pulse structure of the ion beam. This disadvantage can be avoided when the beam is completely space charge and current neutralized, and when the focusing magnetic field is generated by a high current discharge.

This concept of an active plasma lens has the additional advantage that it can be experimentally tested with beams of low intensity. Active plasma lenses have usually been used as 'thin' lenses [2-4]. 'Thin' in this context means that the beam passage through the lens require less than one-quarter of a betatron oscillation. A thin lens is characterized by the fact that the focal length of the lens depends on the phase of the betatron oscillation that the particles have reached at the end of the lens. Particles of different energy or charge state are focused to different points. If the focal point is close to the end of the lens, then the beam diameter inside the discharge plasma changes significantly. In this case, the efficiency of the lens can be enhanced by fitting the discharge diameter to the beam envelope.

This can be achieved by tapering the discharge tube and does not affect the ion optical properties of the lens [5]. Such a tapered lens with an adiabatically slow increase of the focusing power can be used as a thin or as a thick lens. A thick adiabatic lens is characterized by the fact that the field creating discharge has a length of typically several betatron wavelengths. In this type of lens, a reduction of the beam envelope can be achieved independent of the phase of the beam particles at the end of the lens [6]. This provides the possibility of focusing beams with a high momentum spread or beams with particles in mixed charge states. The smallest diameter for a beam of high momentum spread is exactly at the end of the lens. In general, the beam diameter increases rapidly behind the lens. Therefore, it is not possible to have a stand-off distance from such a lens to a target. For an adiabatic lens, certain relationship for the lens aperture, the beam radius at the lens entrance and the desired final beam radius have to be fulfilled.

In the adiabatic lens, the beam envelope is described by Hill's equation [7]

$$\frac{d^2r}{dz^2} = -k^2 r \quad \text{with} \quad k^2(z) = \frac{Z(z)}{a^2(z)} \frac{2eI}{\beta mc^3}$$

Here, Z denotes the charge state of the ion, I is the total discharge current in the lens and a is the radius of the focusing discharge. In the adiabatic approximation

$$\frac{1}{k^2}\frac{dk}{dz} \ll 1$$

a solution can be written in the form

$$r = \frac{C}{k^{1/2}} \exp\left(i \int k \, dz\right)$$

If the ratio of the beam radius at the end of the lens (r_{out}) and that the entrance of the lens (r_{in}) is $b = r_{out}/r_{in}$, then the initial wave number k_{in} has to be decreased by a factor of b^2 to $k_{out} = k_{in}/b^2$ at the end of the lens, to reduce the radius of the beam envelope (r) by a factor of b. To achieve a beam size reduction of $b = 3$ for typical parameters of a driver beam with $m = 200$ a.m.u. and $\beta = 0.3$, with a discharge current of $I = 100$ kA, and assuming that the beam is stripped from initially $Z = +16$ to $Z = +64$ at the end of the lens, the channel has to be tapered down from the entrance radius $a_{in} = 11.25$ mm to an exit radius $a_{out} = 2.5$ mm. This yields a reduction of the beam

Table 1
Capabilities of different lenses for a fusion reactor

	Reactor requirement	Quadrupole lens	Thin plasma lens	Adiabatic lens
Aperture	Small	Large	Small	Small
Stand-off distance (m)	≈ 5 m	>5 m	<1 m	<0.1 m
Focusing ratio	≈ 20	>20	>50	≤ 5
Achromaticity	High	Low	Low	High
Sensitivity to emittance	Low	High	High	Low
Max, beam current (kA)	≈ 100	<10	>100	>100

radius from $r_{in} = 7.5$ mm to $r_{out} = 2.5$ mm. The admissible emittance for the beam is determined by the conservation of phase space density over the simple relation $\varepsilon/r = ka$, which allows a normalized emittance of 62 mm mrad for the above example.

3. Requirements for a final focus system in a fusion reactor

The final focus system for a fusion reactor has to focus several beams with a total current of about 100 kA, and with radii of the order of 100 mm, to a focal spot of a few millimeters in radius. The beams have a large momentum spread, which is required for the final longitudinal bunch compression. To relax the requirements for the accelerator, the admissible emittance of the driver beams should be as high as possible. Since the reactor chamber has a radius of at least 5 m and the final lens has to be situated outside the reactor, a large stand-off distance is necessary. To simplify the protection of the beamlines from debris in the reactor, the number and area of the entrance ports for the beams should be as small as possible.

Neither conventional quadrupole lenses nor any of the above-mentioned plasma lenses can fulfill all these requirements. Conventional quadrupole lenses require large apertures into the reactor chamber and about 10 lenses to avoid excessive space charge aberrations of the non-neutralized beams over the long drift distance from the end of the last quadrupole to the target. Sufficient achromaticity and insensitivity to beam emittance are difficult to achieve.

A thin plasma lens has a small aperture into the reactor and can transport the total beam current required to drive a target, in a single lens. The beams can be focused to very small spot sizes on a target at small stand-off distances, but only very poor focusing can be expected for a focal length of several meters. Achromatic errors are difficult to correct and the focusing is very sensitive to the beam emittance.

The adiabatic plasma lens meets most of the requirements for a fusion reactor. It has a high achromaticity and insensitivity to beam emittance, and can focus the total driver beam current in a single lens with a small aperture into the reactor chamber. Since the beam size reduction of the adiabatic focusing is limited to ratios of the order of 3-10 to avoid excessive tapering of the discharge, additional prefocusing is required. This can be achieved using a conventional quadrupole lens. The most serious problem of the adiabatic lens is that the beam cannot be extracted from the lens but has to be confined in a transport channel that extends into the immediate vicinity of the target. Nevertheless, the adiabatic focuser is a very interesting alternative to quadrupole focusing, since it significantly reduces the requirements for beam quality of the driving accelerator. The capabilities of the different focusing concepts are summarized in Table 1.

4. Layout of a reactor chamber with adiabatic plasma lens focusing

A possible reactor layout using an adiabatic lens is sketched in Fig. 1. The adiabatic lens as the

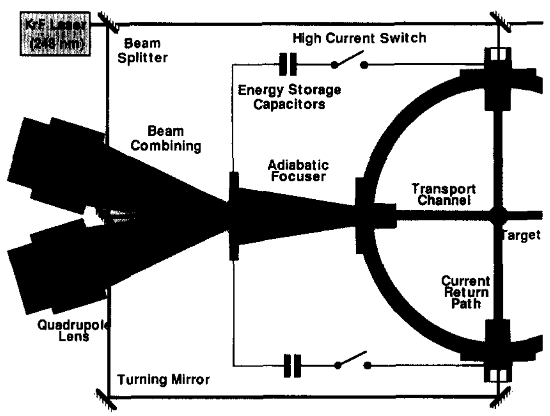

Fig. 1. Schematic layout of a reactor chamber using adiabatic focusing and discharge channel transport.

central element of the final focus system is located immediately outside the reactor chamber. The focused beam is guided from the end of the lens to the target by a discharge channel. The envelope radius of the beam in this channel is the same as at the end of the lens, and determines the spot radius on the fusion target. Because the lens and channels require the same discharge current, they can be driven by a single capacitor bank. One or (to reduce the circuit inductance) several current return paths are required from the target back to the driving capacitor bank. Depending on the allowed non-uniformity of target illumination, one or several focusing systems can be used.

Fig. 1 sketches two transport channels from opposite sides and two return current channels perpendicular to the transport channels. Laser preionization of the background gas in the reactor chamber is used to stabilize and direct the discharge channels. In Fig. 1, an excimer laser produces the preionization channel. A laser pulse energy of the order of 10 J is sufficient for this purpose. Other preionization possibilities are discussed in the following section.

Since the adiabatic lens is not capable of providing a sufficiently high focusing ratio, a conventional quadrupole lens is necessary to prefocus the ion beams from the accelerator to the entrance of the adiabatic lens. A lens that reduces a beam from a radius of 7.5 mm to a spot radius of 2.5 mm on the target needs a length of about 1.7 m to fulfill the adiabaticity condition. This distance is the length of one betatron oscillation at the entrance of the lens, or of nine betatron wavelengths at the exit of the lens, for a discharge current of 100 kA, an ion mass of 200 a.m.u. and a velocity of $0.3c$. A lens of this sort has an acceptance angle of 30 mrad, which allows several driver beams to be combined directly in front of the lens. The space charge neutralization and the insensitivity to beam emittance of the adiabatic lens make the entrance of the tapered discharge an ideal place to combine several driver beams. An additional advantage of beam combining is that it provides a free path for the preionizing laser beam.

5. Possibilities of discharge channel generation for ion beam transport

One possible way to transport tightly focused beams over distances of several meters is propagation in a high current discharge channel. Transport efficiencies close to 100% have been demonstrated for intense light ion beams with beam currents up to 400 kA in wall-stabilized discharges [8,9]. The means to direct and stabilize the required high current discharge channel in a fusion reactor are very limited, since it is desirable to avoid any destructible structures in the reactor chamber that have to be replaced after every ignition of a fusion pellet. Effective guiding of the ion beam is of special importance in the immediate surroundings of the target, where electric and magnetic fields between the transport channels and the current return paths tend to distort the channels. The most promising way to establish stable, straight channels under these special circumstances is the formation of an ionization channel in the background gas of the chamber with a laser. There are different ways to produce these laser channels.

One of these possibilities is to use a CO_2 laser and ammonia (NH_3) as the background gas in the chamber. The laser can be tuned to the molecular vibration frequency of the NH_3 and provides an efficient source to heat the gas in the laser path. Temperatures of about 2000 K were measured for an incident laser energy of the order of 30 J cm^{-2} for a channel of length 50 cm filled with 20 Torr

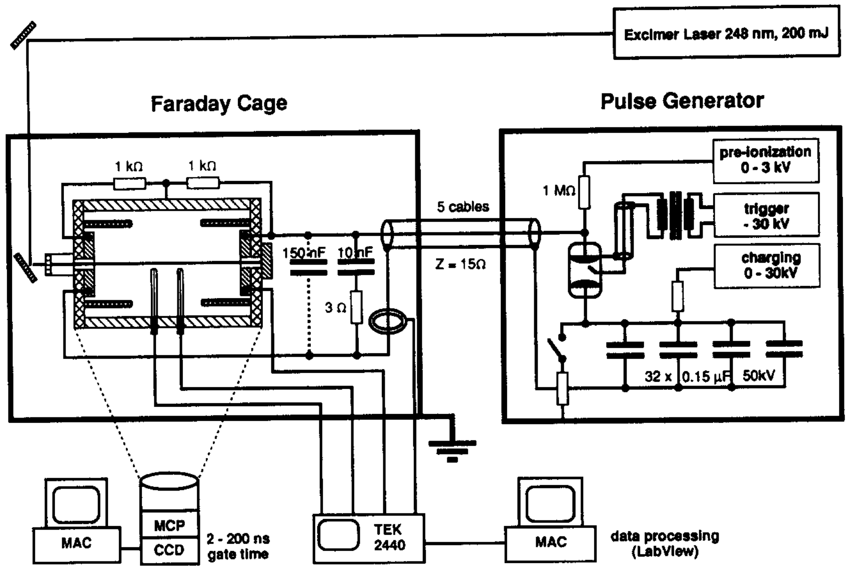

Fig. 2. Experimental set-up used for investigation of discharge channel generation and stability.

of NH_3 [10]. The self-breakdown voltage of a gas chamber can be reduced 10-fold by the formation of this channel [11]. Thermal ionization and rarefaction of the discharge gas in the laser channel are the mechanisms that are responsible for this reduction. Successful channel generation with this method was reported for a length of up to 1.4 m and a current of 18 kA [11]. The development of kink instabilities in the channel is described at currents above 34 kA [12]. Channels 1 m long have successfully used for light ion beam transport with an efficiency of 50% [12].

Another efficient way of coupling laser energy into a background gas is 'laser ionization based on resonance saturation' (LIBORS) [13]. Here, a laser is tuned to the resonance line of an alkali vapor (670.8 nm for lithium). The dense population of atoms in the excited resonance state provides translation energy to produce free electrons by collisions, and a large number of atoms with an ionization energy that is reduced by the excitation energy of the resonsance state. An ionization fraction of 95% was measured in a channel of 15 cm long, produced with a dye laser pulse of 1 MW and duration 800 ns [14]. For a vapor pressure of 0.1 Torr, this results in an electron density of 2×10^{15} cm^{-3} in the laser channel. Experiments in lithium vapor at 0.1 Torr were reported at a chamber temperature of 900 K with an admixture of 5–10 Torr of an inert gas to prevent lithium depositions on the laser entrance windows [15].

A third possible mechanism to create an ionization channel with a laser is to use a two-photon absorption process of UV radiation in organic molecules with high two-photon ionization cross-sections. For the experiments that are described in the paper, a KrF laser with a wavelength of 248 nm was used. Similar results can be expected for a frequency quadrupled Nd-YAG laser at 266 nm. For these wavelengths tripropylamine (TPA) and benzene (C_6H_6) are promising candidates as the absorbing molecules. Data for the two-photon ionization cross-sections, absorption and the influence of buffer gases on the two-photon ionization can be found in Refs. [16,17]. A reduction of the self-breakdown voltage to about 30% of the initial value by the laser preionization was measured for a channel 60 cm long with a laser energy of about 100 mJ in a pulse of 18 ns [18]. In this experiment, the self-breakdown voltage of the Pyrex test cell filled with 25 Torr of NH_3 as a buffer and an admixture of 0.1–1 Torr of the organic component was 36 kV.

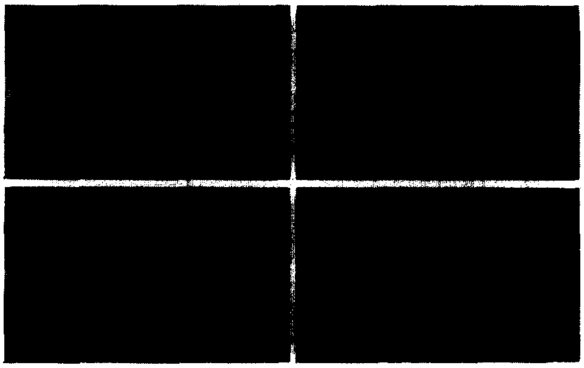

Fig. 3. Discharge channels with a length of 40 cm and a peak current of 10 kA in 1 Torr of benzene at different times after ignition of the discharge.

6. Experimental test of discharge channel generation by laser preionization

The experimental set-up and the available diagnostics to test the generation and stability of laser-preionized discharge channels are shown in Fig. 2. The main difference from the experiment described in ref. [18] is that the d.c. self-breakdown voltage of the discharge chamber is of the order of 1 kV, as a result of the use of a metallic chamber that models a reactor chamber much better than a completely insulating discharge cell. The electrodes are mounted electrically insulated from the chamber on Plexiglas flanges. To prevent an immediate surface breakdown to the metal chamber, which is kept on half-potential between the two electrodes, a Plexiglas ring around the electrodes was used to increase the length of the insulating surface between the electrodes and the chamber from 36 to 236 mm. A KrF laser with a wavelength of 248 nm and a pulse energy of up to 200 mJ in a pulse of 20 ns, focused to a parallel beam of cross-section 3 mm × 10 mm was used for the preionization.

The laser enters the chamber through the central bore diameter 10mm in the hollow anode. To reduce high voltage peaks at the anode after applying the voltage via five 15 Ω pulse cables from the pulse power generator, a 10 nF capacitor in series with a 3 Ω resistor provides an impedance-matched termination for the pulse front. The pulse generator consists mainly of an energy storage capacitor bank with up to 4.8 μF, that can be charged up to 30 kV, along with a triggered spark gap to switch the discharge current. For diagnostics, the total discharge current can be measured with a calibrated Rogowski coil and the magnetic field distribution inside the discharge chamber can be determined with two pick-up coils. By integrating and calibrating the signals from these coils, the current density distribution in the plasma can be reconstructed.

An image-intensified short time charge-coupled device (CCD) camera system with exposure times between 2 and 200 ns was used as a second diagnostic tool. A series of typical pictures from this camera is shown in Fig. 3. The discharge gas for the discharges in Fig. 3 was benzene at a pressure of 1 Torr. The peak current of 10 kA was reached after 3.8 μs. A very stable, straight channel is found at all times. The channel is expanding with a maximum radial velocity of 3.5×10^5 cm s^{-1}. The bright structures in the upper right-hand corner and on the left-hand side of the images are surface breakdowns along the insulating Plexiglas rings from the electrodes to the metal discharge chamber.

How the total discharge current is divided between the surface breakdown and the central, laser-preionized channel depends on the efficiency of the preionization and on the discharge conditions. Increasing the discharge current by charging the capacitor bank to higher voltages increases the peak channel up to a charging voltage of about 9 kV, independent of the peak discharge current, which could be varied independently by changing the capacity of the capacitor bank. Increasing the charging voltage above 9 kV leads to a drop in the peak channel current by about 40%. The channel current remains almost constant at this level up to a charging voltage of 30 kV, and only the current that flows over the insulator surface increases. A possible explanation for this behavior is that the voltage drop over the channel causes the observed breakdown.

To increase the conductivity of the channel and reduce this voltage drop, a capacitor of 150 nF was connected across the discharge chamber in parallel to the switched capacitor bank. This ca-

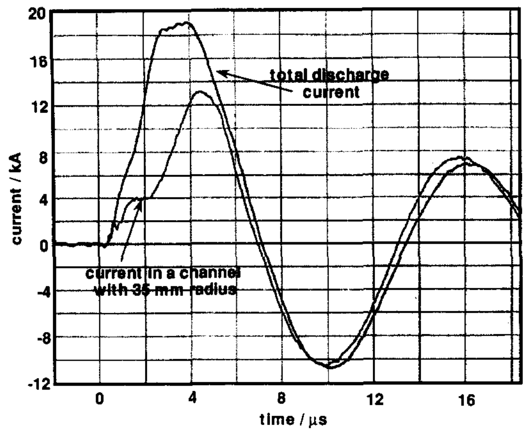

Fig. 4. Total discharge current and current enclosed in a channel of radius 35 mm for a discharge with peak current 19 kA in benzene at 0.32 Torr.

pacitor was charged to the self-breakdown voltage of the gas in the chamber between 0.8 and 1.5 kV, depending on the kind and pressure of the discharge gas. A partial discharge of this capacitor could be triggered by the ionization of the gas with the laser. This discharge improved the preionization in the laser channel and increased the peak channel current during the main discharge of the capacitor bank—which was triggered with a variable delay of 0.5–5 μs with respect to the laser pulse—by 30%–60%.

A time-resolved measurement of the channel current was obtained from the magnetic field probes in the discharge chamber. A typical result from these measurements for a total discharge current of 19 kA is shown in Fig. 4. The figure shows the total current that is flowing inside a channel of radius 35 mm. Variations of the probe position imply that the complete channel current is enclosed in this radius. Up to a current of 2 kA, the discharge current is flowing entirely in the central channel. With increasing current, the difference between the total current and the current in the channel grows, as a result of development of the additional current path over the insulator surfaces to the chamber wall. After 2 μs, when the maximum current of the discharge is reached, only 20% of the total current is flowing in the central channel. From this time on, the current in the channel is rapidly growing until, after about 5 μs, the entire current is flowing in the channel. During the second and third half-waves of the discharge, the current flows completely in the central channel. It can be expected that an improvement of the preionization, by adding an independently switched preionization circuit that can deliver a current of 1–2 kA at a low voltage, can eliminate the breakdown to the chamber wall and will allow the channel current to increase significantly. For currents up to 15 kA, the slowly expanding channels show no hydrodynamic instabilities. Breakdown problems to surrounding grounded structures caused by insufficient conductivity of the preionized channel seem to be more important than hydrodynamic instabilities. Further experiments are planned to increase the channel current by improving the preionization, and to study the channel–target interaction and breakdown problems between the transport channel and a current return channel from the target.

7. Test of an adiabatic plasma lens

The central part of the final focus system described in this paper is the adiabatic plasma lens. One of the most important characteristics of this lens is its capability to focus high emittance beams. Therefore, the focusing properties for high emittance beams and the transmission of the lens are important topics in an experimental test.

An electrostatic quadrupole injector (ESQ) capable of producing a singly charged potassium beam with a current of up to 800 mA at an energy of up to 2 MeV was used to test the focusing properties. The low beam energy caused several experimental problems that do not exist for beams at much higher energies—of several gigaelectronvolts—because they will be used in a fusion driver. One of these problems is that the short ion range in solid matter does not allow any windows in the beam path. For that reason, it was necessary to install a powerful differential pumping system to maintain the injector vacuum. This three-stage system reduced the pres-

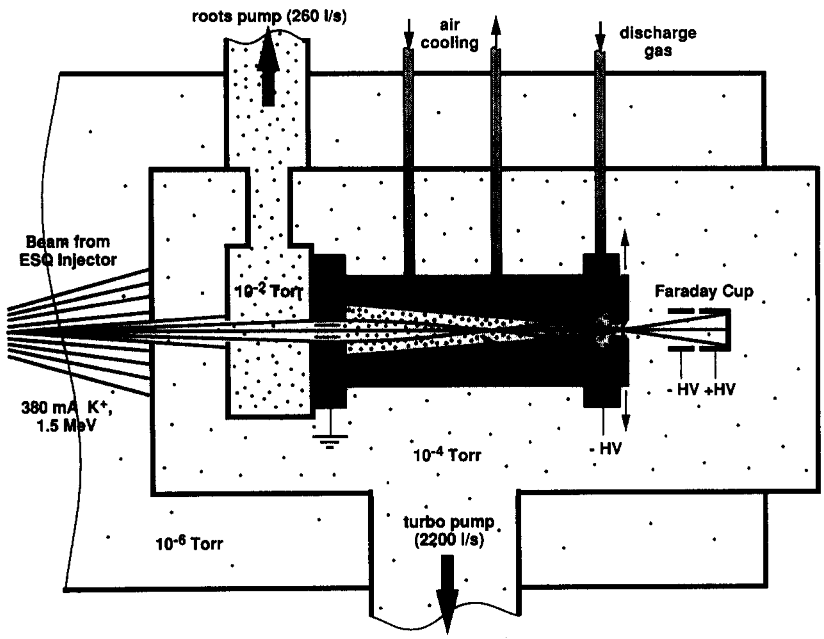

Fig. 5. Experiment to test adiabatic focusing of a 1.5 MeV potassium beam.

sure in the discharge tube from 1 Torr over a distance of 135 mm to 10^{-6} Torr at a free aperture for the beam of 5 mm × 15 mm. Another consequence of the short ion range is that it is not possible to use scintillators to diagnose the focused ion beam, because the separation of the scintillation light from the optical radiation of the discharge plasma is very difficult. Therefore, electrical diagnositcs using a Faraday cup was chosen, which provides a good temporal resolution. Spatial resolution of the beam profile behind the discharge will be achieved by a pinhole that can be moved across the exit aperture of the lens. The diameter of the Faraday cup and the distance from the pinhole were dimensioned in a way that, even for the largest expected divergence angles of the beam behind the lens, the total intensity that is transmitted through the pinhole is measured in the cup. A schematic representation of the plasma lens, the differential pumping system and the diagnostic system is shown in Fig. 5.

Experiments were performed with beams of ion energy 1.1 and 1.5 MeV. The current of 360 mA of the 1.1 MeV potassium beam at the entrance of the differential pumping system is reduced to about 5 mA at the entrance of the discharge. Without discharge gas, the pinhole with a diameter of 0.5 mm at the end of the discharge tube 300 mm long reduces the particle current to a calculated value of 16 μA. The measured value of 21 μA can probably be explained by partial stripping of the ions to a higher charge state, which is (according to Betz [19]) $+1.8$ for 1.1 MeV and $+2.1$ for 1.5 MeV, is reached at only 5×10^{-3} Torr in the discharge tube. A significant increase in the measured electrical current can be expected even at much lower gas pressures. At the working gas pressure of 1 Torr of helium in the lens, the gas is not only stripped but the transmission is also strongly decreased by scattering. The microdivergence of the beam after passage through the gas is 36 mrad (full angle for 90% of beam intensity) and the intensity in the pinhole is reduced to 5.6 μA. By pulsing a current of 5.9 kA through the discharge tube, the beam intensity in the pinhole can be enhanced by a factor of 20 to 112 μA. At the higher ion energy of 1.5 MeV, an enhancement by a factor

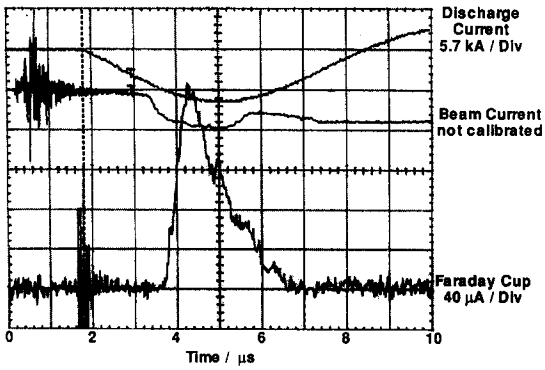

Fig. 6. Beam intensity measured behind a pinhole at the end of the adiabatic lens. Upper trace: discharge current, 5.7 kA div^{-1}; middle trace: ion beam pulse measured with a Rogowski coil before the lens, not calibrated; lower trace: signal from the Faraday cup behind the pinhole at the lens exit, 40 μA Div^{-1}.

of 26 from 7.6 μA to 200 μA was found during the current pulse. In Fig. 6, the discharge current, the signal from a Rogowski coil at the end of the injector and the signal from the Faraday cup are shown for an ion energy of 1.5 MeV. The discharge is ignited at 1.8 and the ion pulse starts at 3.4 μs. Taking into account the 350 ns time-of-flight delay between the position of the Rogowski coil and the Faraday cup, the corresponding two signals start at the same time. The steep rise of the cup signal reflects mainly the rise time of the ion beam pulse. The experimental results are in good agreement with calculations that include the initial beam conditions, stripping and the emittance increase by scattering. The high intensity increase despite the strong scattering of the ions in the discharge gas indicates that the adiabatic focusing is working as expected. Further experiments are planned to measure the transmission through the lens and the intense profile of the beam behind the lens.

Acknowledgements

One of the authors (A.T.) was supported by a Feodor-Lynen fellowship granted by the German Humboldt foundation during his work at the Lawrence Berkeley National Laboratory.

References

[1] D.A. Callahan, Chamber propagation physics for heavy ion fusion, Fus. Eng. Des. 32-33 (1996) 441-452.

[2] E.B. Forsyth, L.M. Lederman and J. Sunderland, The Brookhaven—Columbia plasma lens, IEEE Trans. Nucl. Sci. 12 (1965) 872-876.

[3] R. Kowalewicz, M. Lubrano di Scampamorte, S. Maury, S. Milner, H. Riege, J. Christiansen, K. Frank, U. Neuner, M. Stetter, R. Tkotz, M. Wenninger, E. Boggasch and A. Tauschwitz, Optimizing the CERN plasma lens for antiproton collection, Proc. Int. Conf. on High Energy Accel., Hamburg, 1992, Int. J. Mod. Phys. (Proc. Suppl.) 2A (1993) 182-184.

[4] E. Boggasch, A. Tauschwitz, H. Wahl, K.-G. Dietrich, D.H.H. Hoffman, W. Laux, M. Stetter and R. Tkotz, Plasma lens fine focusing of heavy-ion beams, Appl. Phys. Lett. 60 (1992) 2475-2477.

[5] Tauhschwitz, M. de Magistris, E. Boggasch, W. Laux, M. Dornik, H. Wetzler and D.H.H. Hoffman, Improvement of the active cylindrical plasma lens concept by a tapered discharge geometry, IEEE Trans. Plasma Sci. 23 (1995) 388-392.

[6] P.F. Ottinger, D. Mosher and S.A. Goldstein, Propagation of intense ion beams in straight and tapered z-discharge plasma channels, Phys. Fluids 23 (1980) 909-920.

[7] P. Chen, K. Oide, A.M. Sessler and S.S. Yu, Plasma-based adiabatic focuser, Phys. Rev. Lett. 64 (1990) 1231-1234.

[8] F.A. Sandel, S.J. Stephanakis, F.C. Young and W.F. Oliphant, Experimental studies of intense light-ion beam transport, Proc. 4th Int. Conf. on High-power Electron and Ion Beams, Palaiseau, 1981.

[9] J.M. Neri, J.R. Boller, G. Cooperstein, D. Mosher, P.F. Ottinger, V.E. Scherrer, F.A. Sandel, S.J. Stephanakis, F.C. Young, P.J. Goodrich and D.D. Hinshelwood, Transport and focusing of intense light-ion beams for ICF with Z-discharge plasma channel, Proc. Int. Conf. on High-power electron and Ion Beams, Karlsruhe, 1988.

[10] J.N. Olsen, Laser-initiated channels for ion transport: CO_2-laser absorption and heating of NH_3 and C_2H_4 gases, J. Appl. Phys. 52 (1981) 3279-3285.

[11] J.N. Olsen and L. Baker, Laser-initiated channels for ion beam transport: breakdown and channel evolution, J. Appl. Phys. 52 (1981) 3286-3292.

[12] J.N. Olsen and R.L. Leeper, Ion beam transport in laser-initiated discharge channels, J. Appl. Phys. 53 (1982) 3397-3404.

[13] R.M. Measures, N. Drewell and P. Cardinal, Electron- and ion-beam transportation channel formation by laser ionization based on resonance saturation—LIBORS, J. Appl. Phys. 50 (1979) 2662-2669.

[14] T.J. McIlrath and T.B. Lucatorto, Laser excitation and ionization in a dense Li vapor: observation of the even-parity, core-excited autoionizing states, Phys. Rev. Lett. 38 (1977) 1390-1393.

[15] A. Young, M.Y. Mirza and W.W. Duley, Multiphoton ionization spectra in lithium vapour, Optics Commun. 31 (1979) 157–160.

[16] L.C. Lee and W.K. Bischel, Two-photon-ionization coeffcients of propane, 1-butene, and methylamines, J. Appl. Phys. 53 (1982) 203–207.

[17] J.R. Woodworth, T.A. Green and C.A. Frost, ionization of organic molecules with ultraviolet lasers: a technique for generating large, well-defined ionized volumes, J. Appl. Phys. 57 (1985) 1648–1655.

[18] C.A. Frost, J.R. Woodworth, J.N. Olsen and T.A. Green, Plasma channel formation with ultraviolet lasers, Appl. Phys. Lett. 41 (1982) 813–815.

[19] H.D. Betz, Heavy ion charge states, Appl. Atomic Collision Phys. Pure Appl. Phys. 43 (1983) 1–42.